

THE WORLD OF CHEMISTRY

Program #11

THE MOLE

Producers Linda Moulton Howe
and Stephen Redhead

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Babies in Africa,
IV bag, children in hospitals,
making IV solutions

NARRATOR (MUSIC and NAT
SOUND under):

Human lives can depend on the exact
science of chemistry. From the familiar
IV bag, salts and sugar pass into the
bloodstream. They act at a molecular
level so the body's cells can function
again. How can we produce, on a
factory scale, substances that work so
accurately at a molecular level? How
can we mix just the right amounts for
the molecular world we cannot even see?
To do this, in laboratory and in
industry, chemists use a concept called
the mole.

SUPER: THE MOLE

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in office sitting
at a desk

ROALD HOFFMANN (SYNC):

At the heart of chemistry is synthesis, the making of molecules. At the beginning of any chemical reaction, there are reactants; at the end, there come out products. Now, a caricature of a way of making molecules is to take the reactants, mix them together, beat on them with heat, or light, or some other source of energy, and then, in an explosion, a flash of light and smoke, the product materializes. That's the way it goes in comic books, but that's not the way that any chemical company is going to make a cent of profit. Into any modern chemical process there goes planning, whether it is into the making of ammonia, or of aspirin, or of a beautiful molecule shaped like a tube, for which no use has as yet been found. Into any of these, there goes careful planning. Precise amounts of reactants have to be weighed out. Too little and the reaction might not go. Too much, and there is going to be something left over, waste. How does a chemist know precisely how much is right?

Microscopic shots,
chemist working
in lab

NARRATOR (NAT SOUND under):
Today, chemists know how much is
right because they can count the
fundamental particles of matter, atoms
and molecules. It is now possible to
connect the macroscopic world that we
can see with the invisible molecular
world. In short, chemists have learned
how to count molecules by weighing
macroscopic amounts.

Chemist working in
antique laboratory

NARRATOR (MUSIC and NAT
SOUND under):
Two hundred years ago, scientists
weren't even sure what atoms and
molecules were, let alone being able to
count them. For Berzelius, an
outstanding analytical chemist of the
19th Century, a major problem was
obtaining accurate atomic masses. One
needed to know how much of each
element combined, the combining
masses, and the correct formula for the
compound. Berzelius was one of the
pioneers in this effort.

Periodic table graphic,
balloon blowing up

NARRATOR (MUSIC and NAT
SOUND under):

Nowadays, even a beginning chemistry student can calculate a formula, using analytical data and the atomic masses found in the periodic chart. How has this come about? The initial breakthrough came from the study of gases.

GRAPHICS: Volumes and
numbers of molecules in
a gas reaction

NARRATOR (MUSIC and NAT
SOUND under):

Here is a gas reaction like one they did then. One volume of hydrogen gas is released into a clear balloon, then one volume of chlorine into another balloon. The valve is opened so the two gases mix together. When a light is shined on them, there's a chemical reaction to form two volumes of a new compound, hydrogen chloride. Note one volume plus one volume produced two volumes. As you know, chemists learned that all gases react in small, whole-number ratios. What principle lay behind this gas law, stated in 1808? What is happening at the molecular level? The Italian scientist, Amadeo Avogadro, pondered these questions. (cont.)

NARRATOR cont:

In 1811, he proposed that equal volumes of different gases, at the same temperature and pressure, contain equal numbers of molecules. Now we understand Avogadro's insight. We know why gases react with each other in simple ratios. A molecule of chlorine gas is made of two atoms, and a molecule of hydrogen gas is also made of two atoms. When the gases combine, one volume to one volume, two volumes of the hydrogen chloride molecule are produced. In gases, there is a simple relationship between numbers of particles and volume. Therefore, if we measure the mass of equal volumes of different gases, at the same temperature and pressure, we can easily calculate the relative masses of the molecules, since there are an equal number of molecules in each case.

MONTAGE: Hot air
balloon, slow motion
drop of water, crystals

NARRATOR (MUSIC and NAT
SOUND under):

So, in gases, the determination of relative masses is quite straightforward, but determining the relative atomic masses of solids and liquids requires more ingenious methods. Let's take a closer look at the problem of the relative masses of solids and the notion of counting by weighing. Don Showalter.

DS in lab

DON SHOWALTER (SYNC):

We have in front of us here a balance that chemists use to weigh chemicals. The weight will be read out here in grams. However, rather than just weighing chemicals, let's weigh something we all like. Let's weigh some money. I have a quarter. One quarter weighs 5.7 grams. Let's weigh one penny. The penny weighs 2.5 grams. If we wanted to determine the relative weight of the two coins, we would divide the weight of the quarter by the weight of the penny. If we do that, you see that we come up with a value that shows that the quarter is about twice as heavy as the penny. Now let's weigh this pile of 20 quarters. It weighs 111.9 grams. Now let's weigh this pile of 20 pennies, the same number of pennies. The weight is 51.0 grams. We would want to determine the relative weight of the piles of quarters to pennies, we would do that in the exact same fashion as we did with the single coins. And you see that that ratio comes out the same. The same principle of relative weights that we've done with the pennies and quarters applies also to the molecular world, even though we can't see molecules or atoms. I can't pick up an atom or a molecule and put it on that balance, but I can pick up a huge number of atoms or molecules and weigh them. (cont.)

DON SHOWALTER cont:

Now, here is something we can see and weigh. It's the element carbon. It's this black powder in here. Let's see how much this carbon weighs. I'll put a dish on there to protect the balance, cancel out the weight of the dish, and we weigh the amount of carbon. It's 12.0 grams, an important weight to remember. If we wanted to compare the weight of another element with the weight of carbon, we would have to have exactly the same number of atoms of that element as there is in this 12 grams of carbon, just as we did with the quarters and pennies. We had to have an equal number of quarters and pennies to compare the relative weights. What is the number of atoms of carbon in that material, 12 grams of carbon? That number is what the chemists call a mole. A mole is the chemist's unit of measure, just as the dozen is the baker's. The mole isn't a single molecule or a single atom it's a huge number of atoms or molecules, and it's always the same number, just like the dozen is always 12. But the mole is much larger than the dozen. It's 6.02 times 10 to the 23rd. That's what we call Avogadro's number. How big is Avogadro's number?

GRAPHIC: Avogadro's
number analogy

NARRATOR (MUSIC under): A
molecule is so small we can't even see it,
but if it were the size of a single grain of
sand, one mole of sand would cover a
city the size of Los Angeles 600 meters
deep.

Chemist working with
scale, computer room

NARRATOR (MUSIC and NAT
SOUND under):
So, the mole is a unit of measurement.
It's a number, an inconceivably large
number. It is determined
experimentally and not by counting.
Can you imagine that a computer,
counting 10 million atoms a second,
would take 2 billion years to count out
one mole? The mole allows chemists to
count molecules and atoms by weighing
the mass of vast numbers of these
particles.

Copper wire, water in
beaker, red balloon

NARRATOR (MUSIC and NAT
SOUND under):
This is a mole of copper. This is a mole
of water. And this is a mole of
hydrogen gas. All have different
masses, but each contains exactly the
same number of particles, trillions and
trillions of them, but exactly the same
number, Avogadro's number, one mole.

GRAPHIC: The mass of
a mole of elements and
compounds

NARRATOR (MUSIC under):

The mass of a mole of any element is equal to the element's atomic mass expressed in grams. These are the relative atomic masses of the elements in the periodic table, based on assigning carbon a mass of 12 units. Let's use the periodic table for some examples.

Here's copper. Its relative atomic mass is 63.5. A mole of copper weighs 63.5 grams. Let's see another element.

Here's magnesium. Its relative atomic mass is 24.305. A mole of magnesium weighs 24.305 grams. The same principle applies to compounds. Here's a water molecule, H_2O . The relative atomic mass of oxygen is 15.999. The relative atomic mass of hydrogen is 1.008. If we add these atomic masses together, one mole of water will weigh 18.015 grams.

DS in lab

DON SHOWALTER (SYNC):

And so we see how we can go from the number of particles to the number of moles, and then to the weight of a substance. Now we have some real, live moles. Each of these substances is a mole -- sugar, water, carbon, copper, and hydrogen. They all have different weights, but they all are made up of Avogadro's number of particles.

Computer graphic,
crystals

NARRATOR (MUSIC and NAT
SOUND under):

The mole, then, is the crucial link
between the invisible molecular world
and the chemical elements and
compounds that we can see and measure.

GRAPHIC (EQUATIONS)

NARRATOR:

Through an understanding of the mole,
the chemical equations used to describe
reactions represent an extremely
informative kind of chemical shorthand.
This equation tells us the number of
molecules that react and the number of
molecules formed, the number of moles
that react and the number of moles
formed. And using the relative atomic
masses, the weights of the reactants, and
the products. With the mole, chemistry
has become an exact and quantitative
science.

Exterior: Baxter Travenol
labs, working in labs,
mixing IV bags, IV in
use in hospital

NARRATOR (NAT SOUND under):

The largest manufacturer of intravenous
fluids in the world is Baxter Travenol,
Incorporated. As in other chemical
plants across the country, chemistry is
carried out here on an enormous scale.
(cont.)

NARRATOR cont:

IV solutions are prepared by pouring bags of chemicals, in this case the sugar, dextrose, and salt, into a huge mixing tank containing distilled water. There is little room for error. The cells in our body depend on precise molar quantities of molecules and ions to function correctly. The wrong balance can destroy those cells. So, each batch of IV solution has to meet exact medical specifications. Chemist Johnny Long.

INTERVIEW: Johnny Long,
chemist, Baxter Travenol

JOHNNY LONG (SYNC/VO):

We have many codes registered with the Food and Drug Administration. The one we're mixing today is a salt and sugar combination batch which contains 4.5 grams of sodium chloride, or salt, per liter of distilled water, and 50 grams of dextrose, or sugar, per liter of distilled water. These weights are added to a known volume of distilled water in our mixing tanks.

Chemists mixing, testing
and analyzing IV solution

NARRATOR (NAT SOUND under):

Quality control is vital. Before the IV bags are filled, a sample of the solution is withdrawn and analyzed to make sure the correct amounts of sugar and salt are present. This is where the mole comes in. (cont.)

NARRATOR cont:

Here the chemist is analyzing the amount of sodium chloride in the sample. The procedure involves titrating a sample of IV solution with a standard solution containing one-tenth of a mole of silver nitrate per liter.

GRAPHIC (EQUATIONS)

NARRATOR:

Let's look at the equation for this reaction. We see that one mole of silver nitrate reacts with one mole of sodium chloride to produce a white precipitate of silver chloride and soluble sodium nitrate.

Chemist working in lab,
calculating moles, filling
IV bags

NARRATOR (NAT SOUND under):

Using a burette, which makes precise measurements of volume possible, silver nitrate is added until all the sodium chloride has reacted, as shown by the color change in the indicator. The chemist then reads off the volume of silver nitrate added, from which she can calculate the number of moles used, which equals the number of moles of sodium chloride present in the sample. This number can then be expressed in grams of sodium chloride per liter of IV solution. (cont.)

NARRATOR cont:

A comparison with the specifications tells the analyst whether or not the IV solution is within acceptable limits. If so, the tank solution is released to fill the IV bags.

INTERVIEW: Johnny
Long cont.

JOHNNY LONG (SYNC):

This is one of our IV bags. As you can see, our label for this particular code states that each 100 milliliters contains 5 grams of dextrose and 450 milligrams of sodium chloride.

Chemists mixing
IV solution

NARRATOR (NAT SOUND under):

That label translates back to the mixing process and the careful analysis.

Weighing on scale,
solution spinning

NARRATOR (MUSIC and NAT
SOUND under)

Counting by weighing. The mole is ubiquitous in chemistry. It gives us a window through which we can glimpse the molecular changes that accompany chemical reactions.

DS in lab

DON SHOWALTER (SYNC):

Remember that original question, how much of which? Well, to see what that means, let's perform a chemical reaction. In these three flasks I have equal amounts of hydrogen chloride dissolved in water. Each one contain a tenth of a mole of hydrogen chloride. Each of the balloons have differing amounts of magnesium. This balloon has a tenth of a mole of magnesium. This one has half as much, and this one has a quarter as much. I will empty the magnesium into the hydrogen chloride, form magnesium chloride and generate hydrogen gas. That will blow the balloon up. Which one of the balloons do you think will inflate the most, the one with the most magnesium in it? Well, let's try it and see. We'll introduce the magnesium into the hydrogen chloride. You see now that hydrogen is being given off. The balloon is inflating. Let's start the other ones, too. Again you see hydrogen gas giving off. Magnesium chloride is formed inside the flask, but it is soluble in the water, so we really don't see it very much. Let's try this one. Now remember, this one had a small amount of magnesium in it. This one had the most, .1 moles. This one had half as much, and this one had one quarter as much magnesium. The reaction is completed. (cont.)

DON SHOWALTER cont:

These balloons are very much the same size. This one's only half the size. We can explain the difference here, because this had half as much magnesium as this one. But why are these two balloons the same size?

EQUATIONS over
still lab shots

NARRATOR (NAT SOUND under):

The answer lies in the chemical equation for this reaction. For every one mole of magnesium we need two moles of hydrogen chloride to complete the reaction. Here are the results of our experiment. The green balloon had equal mole amounts of magnesium and hydrogen chloride. The hydrogen chloride was used up. But a lot of magnesium was left over. In the flask with the yellow balloon, the ratio was twice as much hydrogen chloride as magnesium, which is the 2-to-1 ratio we needed for the most efficient reaction. In the flask with the blue balloon, there was too little magnesium to consume all the hydrogen chloride. The result: less hydrogen gas and less inflation. When molecules or atoms combine during a chemical reaction, they do so in simple molar ratios. (cont.)

NARRATOR cont:

In the magnesium-hydrogen-chloride reaction, this combining ratio is 1-to-2, exactly the amounts present in the amounts present in the reaction with the yellow balloon. The additional magnesium in the green balloon does not change the amount of hydrogen gas produced. Without a corresponding increase in the amount of hydrogen chloride, the additional magnesium remains unreacted.

Chemist working in lab

NARRATOR (NAT SOUND under):

Chemists must use the correct number of moles of reactants in a reaction in order to get the desired amount of product. Sometimes the molar ratio also determines the kind of product. If you use an inappropriate molar ratio of reactants, you end up with a different product.

MONTAGE: Epoxy resins,
construction worker on roof,
auto plant, tin cans on assembly
line, fighter jets, computer
circuit board

NARRATOR (MUSIC and NAT
SOUND under):

Take epoxy resins. We use them in our homes as adhesives. Due to their unique combination of properties, toughness, excellent strength and adhesion, and resistance to other chemicals, (cont.)

NARRATOR cont:

they are widely used as coating and structural materials. Food and beverage cans are coated with epoxy before the contents are added, so as to protect them from the metal. Fighter jets are held together with epoxies. Even computer circuit boards are made using epoxy. But their properties depend on their molecular structure, and this, in turn, relies on combining the correct amounts of other chemicals.

Interior shots at Dow
Chemical, lab shots

NARRATOR (MUSIC and NAT
SOUND under):

Here at Dow Chemical, in Freeport, Texas, an important class of epoxies used as coatings is made by reacting liquid epoxy resin of low molecular mass with bisphenol-A, an advancing agent. The object is to have the two combine to form large epoxy molecules, each with a very high molecular mass, in a process called polymerization. The higher the molecular mass of this epoxy, the more desirable its properties. The relative amounts of each reactant are crucial to this process. John Massingill is a research and development chemist at the plant.

INTERVIEW: John Massingill,
research and development
chemist, Dow Chemical,
Freeport, Texas

SUPER: John Massingill

JOHN MASSINGILL (SYNC):

In order to build a maximum toughness into our final coatings, we combine liquid epoxy resin and bisphenol-A in equal numbers of molecules, and this is where the mole concept comes into our practical world of chemistry at an industry.

Lab shots

NARRATOR:

Massingill uses the mole to convert numbers of molecules into mass.

INTERVIEW: John
Massingill cont.

JOHN MASSINGILL (SYNC):

From the mole concept, we know that using the molecular weight in grams of each of the combined materials, we can get equal molar quantities. So, in terms of the liquid epoxy resin, the molecular weight is 343. So we use 343 grams of the liquid resin. With the bisphenol-A the molecular weight is 228 grams. So the combining ratio is 228 grams to 343 grams. When those are reacted in those ratios, we will get a very high molecular weight.

Shots in lab, shots of
epoxy and titration

NARRATOR (NAT SOUND under):
During the production of this epoxy,
samples are taken and analyzed by the
quality control lab to make sure the
product has a sufficiently high molecular
mass. This analysis involves titration.
Once again, the mole comes into play,
allowing the analyst to equate numbers
of moles with mass. Too much of either
reactants results in an unacceptable
product. Only by combining equal
numbers of moles of the liquid epoxy
and bisphenol-A is a solid epoxy resin
with the correct properties produced.

INTERVIEW: John
Massingill cont.

JOHN MASSINGILL (SYNC):
So using the mole concept, we're able to,
in the laboratory, in the real world of
chemistry, to measure out numbers of
molecules that we need for our chemical
reactions.

MONTAGE: Factory,
work in lab

NARRATOR (MUSIC and NAT
SOUND under):
No matter what the scale, the mole helps
us understand chemical change. It points
to the essential arithmetic that
accompanies all chemical reactions. It
tells us how much we have and how
much we need.

SUPER: THE MOLE

MONTAGE: Chemical reactions,
lab demonstrations, lab work,
program graphics, microscopic
shots

NARRATOR (MUSIC under):

To review, modern chemistry is a quantitative science. During chemical reactions molecules, atoms, and ions, those unimaginably tiny entities, combine in exact whole-number ratios. Chemists have found a way of counting these particles, not individually, but by weighing huge numbers of them. The counting unit is the mole, Avogadro's number, 6.02×10^{23} . Whether a gas, liquid, or solid, element or compound, one mole contains that enormous number of particles. The mass of one mole of any element is equal to the element's atomic mass expressed in grams. One mole of a compound has a mass equal to that compound's molecular mass. The mole allows chemists to move between the invisible molecular world and the macroscopic world, whether in medicine or in industry, in the lab, or in full-scale production.

RH in laboratory

ROALD HOFFMANN (SYNC):

The mole: a simple idea, many practical uses. Imagine you're a farmer; you've cut down an acre of corn and in that corn are 6 kilograms of phosphorous needed by the plant essential to us. So you know you have to replace that phosphorous in the soil before you plant. You go to the store and you see a fertilizer called super-phosphate. You read Calcium 3, Phosphorous 2, Hydrogen 14, Sulphur 2, Oxygen 21. How much of it should you buy? A pound? A ton? The simple arithmetic of the mole tells us how much. Or imagine you're a chemist -- I'm a chemist. Someone tells me to make some titanium disulfide, TiS_2 . Do I take a gram of titanium and two grams of sulphur? No. I take a mole of titanium and two moles of sulphur. Were I to take some other proportions for instance three moles of sulphur, I'd get a different compound, titanium-trisulfide. What's important about this is not that an expert, a chemist, can figure it out, it's that others can -- you can -- think about that.

Credits, Closing Montage, Closing Music

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